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AN INVESTIGATION OF THE RELATIONSHIP  
BETWEEN THE NATURAL PITCHING PERIOD  
OF A SHIP AND THE  
HULL FORM PARAMETERS

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AN INVESTIGATION OF THE RELATIONSHIP BETWEEN THE NATURAL  
PITCHING PERIOD OF A SHIP AND THE HULL FORM PARAMETERS

by

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and  
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ABSTRACT

AN INVESTIGATION OF THE RELATIONSHIP BETWEEN THE NATURAL  
PITCHING PERIOD OF A SHIP AND THE HULL FORM PARAMETERS

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Submitted to the Department of Naval Architecture and Marine Engineering on May 26, 1958 in partial fulfillment of the requirements for the degree of Naval Engineer and the Degree of Master of Science in Naval Architecture and Marine Engineering.

The purpose of this thesis was to investigate the relationship between the natural pitching period of a ship and the hull form parameters. A theoretical relationship was developed by using simple geometric forms as approximations for the sectional area curve and the waterplane shape. This resulted in the formula:

$$T_p / \sqrt{L} = C_k \sqrt{\frac{\Delta}{(.01L)^3}}$$

where  $C_k$  is a function of  $C_p$ ,  $C_w$ ,  $L/H$ ,  $L/B$  and the ratio of the length and beam of the submerged volume to the waterline length and beam. The accuracy of the theoretical relationship was determined by predicting the period-length ratio and comparing it with the values computed for 79 ships of various types and 6 hull forms. Good agreement was obtained for the great majority of cases.

The theoretical relationship was used to show that the important methods of decreasing the period-length ratio at any displacement-length ratio are to increase the draft and the waterplane area. Due to past practices in ship design an empirical relationship for the period-length ratio versus displacement-length ratio exists. It is also possible to markedly increase the natural pitching period to a value where supercritical operation becomes feasible at normal speed-length ratios. This can be done by decreasing the waterline length and beam in relation to that of the maximum dimensions of the submerged volume.

Further study should investigate the effect of ship velocity on the coefficient of accession to inertia. The effect of damping, coupling to heave and large angles of pitch on the natural pitching period should also be investigated. A feasibility study of a vessel for supercritical operation is also recommended.

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## INTRODUCTION

The pitching motion of ships has been receiving increasing attention as the result of studies in the field of seakeeping. One of the more recent theories concerning the seakeeping of ships is that presented by E.V. Lewis [7]. This theory is based on recent oceanographic studies and several assumptions which appear to be valid. The results of the oceanographic studies indicate that a rough sea can be closely approximated by the superposition of seas of all wave lengths.

In the development of his theory, Lewis assumes that a ship will be in a critical condition as far as pitching motions are concerned when heading into a sea which has waves of length equal to that of the ship and with the period of encounter with this wave equal to the ship's natural pitching period. This synchronism would result in magnification of the pitching motion of the ship. In this condition, the ship will usually be forced to decrease speed or change course to prevent slamming or the shipping of seas over the bow. Since the length of the wave determines the speed of the wave, the natural pitching period of the ship determines the speed at which the ship can move before it reaches this critical condition of operation.

In further developing this theory, Lewis [7] uses a rough approximation to show that the  $T_p / \sqrt{L}$  ratio for a ship varies with the displacement-length ratio. This approximation has been questioned and the data upon which it is based appears to be inconclusive. The purpose of this thesis is to further investigate the relationship between the natural pitching period of a ship and its hull form parameters and thereby clarify this questionable point in the theory presented by Lewis [7].

The formula for computing the natural pitching period of a ship is derived from the simple equation of pitching motion:

$$I_y \frac{d^2\theta}{dt^2} + \rho g J_y(\theta) = 0 \quad (1)$$

This equation implies several basic assumptions which are not necessarily valid. They are:

1. The damping of motion of the hull has a negligible effect on the natural pitching period.
2. The coupling of pitching motion to heave has a negligible effect on the natural pitching period.





3. The velocity of the ship has a negligible effect on the natural pitching period.
4. The motion in pitch is limited to small angles.

The damping of motion has been shown to have only small effect on the natural undamped period in studies of simple harmonic motion. This holds true as long as the magnitude of the damping is small which is the case in the pitching motion of a ship. This assumption is accepted for this study since no contrary information is available.

The coupling of motion between pitch and heave is a result of the assymetry of the hull form and the forward velocity of the ship. A great deal of study remains to be done in the field, but to date, there is no indication that the effect of coupling causes an appreciable effect on the natural pitching period as computed by the simple equation (1). This effect, therefore, has been neglected in this study.

There is definitely some effect on the natural pitching period due to the forward velocity of the ship. This velocity can be expected to affect the correction for the accession to inertia of the entrained water, the damping of the hull form and the coupling of motion between heave and pitch. To date, the magnitude of the change in the natural pitching period due to the ship's velocity is unknown. Any correction for this effect can only be neglected until much more work is done in this field.

The need for a correction for the accession to inertia due to the entrained water was first stated by Kriloff [5]. Methods of determining this factor have been given by F. M. Lewis [8], by G. Vedeler [14], and by Weinblum and St. Denis [16]. This last correction is computed for a completely submerged ellipsoid, but apparently gives satisfactory results for surface ships. It is favored by J. C. Niedermair [10]. This form of the correction for accession to inertia has been used in this study.

A further ramification of the theory presented by Lewis [7] is the fact that ships do not have to operate in the sub-critical range previously described. If the speed of a ship is increased above the critical speed, the ship will enter into synchronism with waves of length greater than the ship's length. This condition can be even worse than the critical condition if the waves of this length have greater energy and thereby represent a greater exciting force. If the speed of the ship can be increased further, however, the ship will eventually enter into synchronism





with a wave length that has very little energy and therefore, very little exciting force. Lewis [7] called this "supercritical" operation. To achieve this condition, a large  $T_p/\sqrt{L}$  ratio is advantageous. In the range of normal  $T_p/\sqrt{L}$  ratios, a very high speed-length ratio is required. This study investigates abnormal hull forms which are designed to have a very large  $T_p/\sqrt{L}$  ratio for the purpose of attaining "supercritical" operation at lower speed-length ratios.



## PROCEDURE

The formula for the natural pitching period of a ship can be derived from the simple, undamped, uncoupled equation for pitching motion:

$$I \frac{d^2\theta}{dt^2} + \rho g J_y (\theta) = 0 \quad (1)$$

It is, in the usual form:

$$T_P = 2\pi \sqrt{\frac{I}{\rho g J_y}} \quad (2)$$

where  $I$  is the total mass moment of inertia of the ship and  $J_y$  is the moment of inertia of the waterplane area.  $I$  is usually expressed as:

$$I = I_y + k_{yy} I_v \quad (3)$$

where:

$I_y$  is the mass moment of inertia of the weight

$I_v$  is the mass moment of inertia of the displaced volume

$k_{yy}$  is the coefficient of accession to inertia.

$$\text{therefore, } T_P = 2\pi \sqrt{\frac{I_y + k_{yy} I_v}{\rho g J_y}} \quad (4)$$

In normal terms:

$$I_y = \rho \nabla K_y^2$$

$$I_v = \rho \nabla K_v^2$$

where  $K_y$  and  $K_v$  are the gyradii of the load and volume respectively. In addition,

$$k_y = K_y/L \quad \text{and} \quad k_v = K_v/L$$

and  $\nabla = C_B BHL$

where  $B, H$  and  $L$  are the dimensions of the displaced volume used in computing  $C_B$ .

$$J_y = \propto_L B_w L_w^3$$

where  $B_w$  = beam of waterplane

$L_w$  = length of waterplane



Substituting the previously defined relationships in the formula for  $T_P$ :

$$T_P = \frac{2\pi}{\sqrt{g}} \sqrt{\frac{\rho C_B B H L^3 k_y^2 + k_{yy} \rho C_B B H L^3 k_v^2}{\rho B_w L_w^3 \alpha_L}}$$

$$\text{and } T_P = \frac{2\pi}{\sqrt{g}} \sqrt{\frac{B L^3}{B_w L_w^3}} \sqrt{k_y^2 + k_{yy} k_v^2} \sqrt{\frac{C_B}{\alpha_L}} \sqrt{H}$$

There can be no exact relationship between  $k_y$  and  $k_v$  since  $k_v$  is fixed by the shape of the displaced volume while  $k_y$  can be varied by changing the location of loads within the ship. In practice, however, major changes of shape or loading introduce only minor changes in  $k_y$  and  $k_v$ . In addition, similar types of ships will tend to be loaded in a similar manner and the location of the load will be limited by the shape of the hull. It will, therefore, be assumed that an approximate empirical relationship exists such that

$$k_y^2 = c k_v^2$$

Appendix A gives values of  $c$  for various ships.

$$T_P = \frac{2\pi}{\sqrt{g}} \sqrt{\frac{B L^3}{B_w L_w^3}} \sqrt{C + k_{yy}} \sqrt{\frac{C_B H}{L}} \sqrt{\frac{k_v^2}{\alpha_L}}$$

and

$$\frac{T_P}{\sqrt{L}} = \frac{2\pi}{\sqrt{g}} \sqrt{\frac{B L^3}{B_w L_w^3}} \sqrt{(C + k_{yy}) \frac{C_B H}{L}} \sqrt{\frac{k_v^2}{\alpha_L}} \quad (5)$$

In Appendix A an approximate relationship for  $\sqrt{\frac{k_v^2}{\alpha_L}}$  is developed for all ships as

$$\sqrt{\frac{k_v^2}{\alpha_L}} = f = \sqrt{\frac{(2C_P^2 - 2C_P + 1)}{C_w(2C_w^2 - 2C_w + 1)}} \quad (6)$$

$$\frac{T_P}{\sqrt{L}} = \frac{2\pi}{\sqrt{g}} \sqrt{\frac{B L^3}{B_w L_w^3}} \sqrt{(C + k_{yy}) \frac{C_B H}{L}} \quad (f)$$



Defining

$$n = \sqrt{\frac{BL^3}{B_W L_W^3}} \quad (7)$$

$$\frac{T_P}{\sqrt{L}} = \frac{2\pi}{\sqrt{g}} \sqrt{\frac{C_B H}{L} (C+k_{yy})} (f) (n)$$

Formula (8) represents a straight line approximation to Fig. 6 for  $L/B \geq 5$ .

$$k_{yy} = .440 \frac{B}{H} + .0233 \frac{L}{B} - .285 \quad (8)$$

Assuming  $C = 1.00$

$$\sqrt{\frac{C_B H}{L} (C+k_{yy})} = \left[ C_B \left( \frac{H}{L} \right) \left( .440 \frac{B}{H} + .0233 \frac{L}{B} + .715 \right) \right]^{1/2}$$

$$\text{and } \frac{C_B H}{L} = \frac{\nabla}{L^3} \left( \frac{L}{B} \right)$$

$$\sqrt{\frac{C_B H}{L} (C+k_{yy})} = \left[ \frac{\nabla}{L^3} \left( .715 \frac{L}{B} + .0233 \left( \frac{L}{B} \right)^2 + .440 \frac{L}{H} \right) \right]^{1/2}$$

$$\text{and } \sqrt{\frac{C_B H}{L} (C+k_{yy})} = \sqrt{35 \times 10^{-6}} \sqrt{.715 \frac{L}{B} + .0233 \left( \frac{L}{B} \right)^2 + .440 \frac{L}{H}} \sqrt{\frac{\Delta}{(.01L)^3}}$$

$$\text{and } \sqrt{\frac{C_B H}{L} (C+k_{yy})} = \sqrt{35 \times 10^{-6}} \sqrt{\frac{\Delta}{(.01L)^3}} (h) \quad (h)$$

where  $h$  is defined as

$$h = \left[ .715 \frac{L}{B} + .0233 \left( \frac{L}{B} \right)^2 + .440 \frac{L}{H} \right]^{1/2} \quad (9)$$

$$\frac{T_P}{\sqrt{L}} = \frac{2\pi}{\sqrt{g}} \sqrt{35 \times 10^{-6}} (f) (h) (n) \sqrt{\frac{\Delta}{(.01L)^3}}$$





$$\frac{2\pi}{\sqrt{g}} \sqrt{35 \times 10^{-6}} = 0.00655$$

and:

$$\frac{T_P}{\sqrt{L}} = C_K \sqrt{\frac{\Delta}{(.01L)^3}} \quad (10)$$

where  $C_K$  is defined as:

$$C_K = 0.00655 (f) (h) (n) \quad (11)$$

Using formula (10) values of  $C_K$  were determined for a large number of ships from  $T_P/\sqrt{L}$  and the displacement length ratio. Values of  $C_K$  were also predicted by formula (11).



FIGURE I  
PREDICTION OF  $C_K$  ERROR DISTRIBUTION

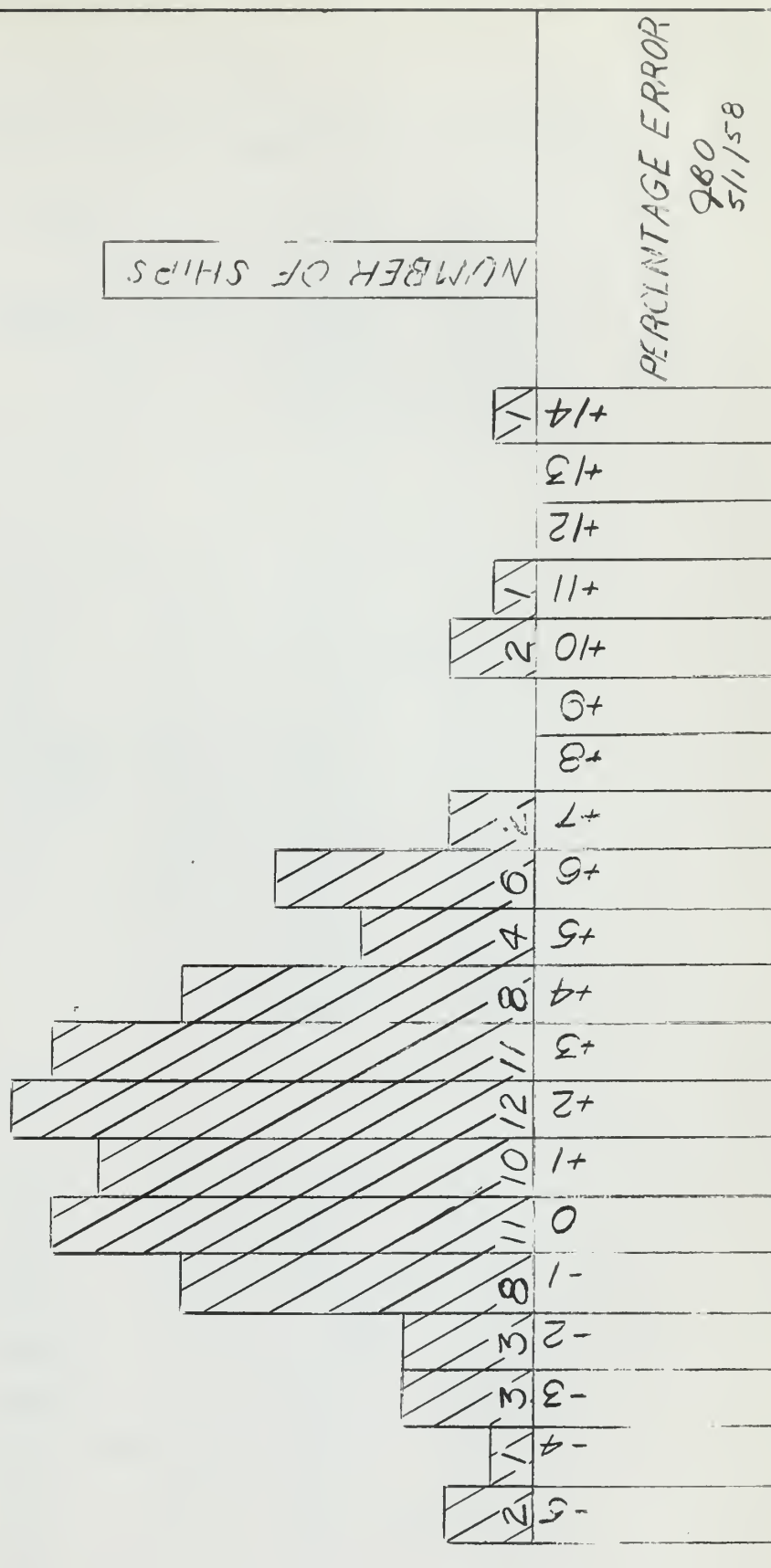




Table I

Specific Ships by Percentage Error in Predicting  $C_K$ 

-5%		-4%		-3%	
CVL-48	No. 17	DD-931	No. 13	DD-348	No. 3
BB-43	No. 50			LST-1153	No. 26
				Passenger	No. 33
-2%		-1%		0%	
DD-692 (LH)	No. 9	CV-Yorktown	No. 6	DD-445	No. 5
CA-32	No. 14	CL-40	No. 8	CA-68	No. 7
LST-1	No. 36	CV-32	No. 16	DD-692 (SH)	No. 12
		CV-2	No. 19	CL-144	No. 15
		Passenger	No. 22	Tanker	No. 56
		Passenger	No. 29	Tanker	No. 57
		LSM-1	No. 37	Tanker	No. 60
		AE-21	No. 45	Cargo	No. 64
				Cargo	No. 68
				Tanker	No. 69
				Ellipsoid	E-1
+1%		+2%		+3%	
DD-356	No. 2	CL-55	No. 10	CA-139	No. 11
PG-50	No. 23	CB-1	No. 18	Barge	No. 24
Passenger	No. 39	BB-61	No. 25	Cargo, Ore	No. 27
Cargo C-4	No. 43	CM-5	No. 28	Passenger	No. 41
Passenger	No. 44	Passenger	No. 30	BB-Penn	No. 48
Tanker	No. 62	Cargo	No. 52	Cargo	No. 49
Cargo	No. 66	Motor Sailer	No. 54	BB-Del.	No. 53
Ellipsoid	E-2	Tanker	No. 55	Cargo	No. 58
Ellipsoid	E-3	Cargo	No. 63	Cargo - C-2	No. 59
Ellipsoid	E-4	Cargo	No. 65	Tug	No. 67
		Tug	No. 74	Tug	No. 78
		Ellipsoid	E-6		



+4%

Cargo	No. 21
Passenger	No. 31
Passenger	No. 32
Cargo	No. 34
Cargo	No. 46
Dredge	No. 71
Trawler	No. 73
Ellipsoid	E-5

+5%

CV-Ranger	No. 1
Ferry	No. 35
Tanker	No. 61
Trawler	No. 70

+6%

CVB-42	No. 20
AD-32	No. 40
Tanker	No. 47
Ferry	No. 51
Tug	No. 75
Tug	No. 79

+7%

CL-51	No. 4
BB-55	No. 38

+10%

Trawler	No. 72
Tug	No. 76

>+10%

Launch	No. 42
Tug	No. 77





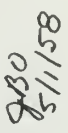
$$C_K \text{ vs. } \Delta / (.01L)^3$$




FIGURE III

$T_p/\sqrt{L}$  vs.  $\Delta/(0.01L)^3$

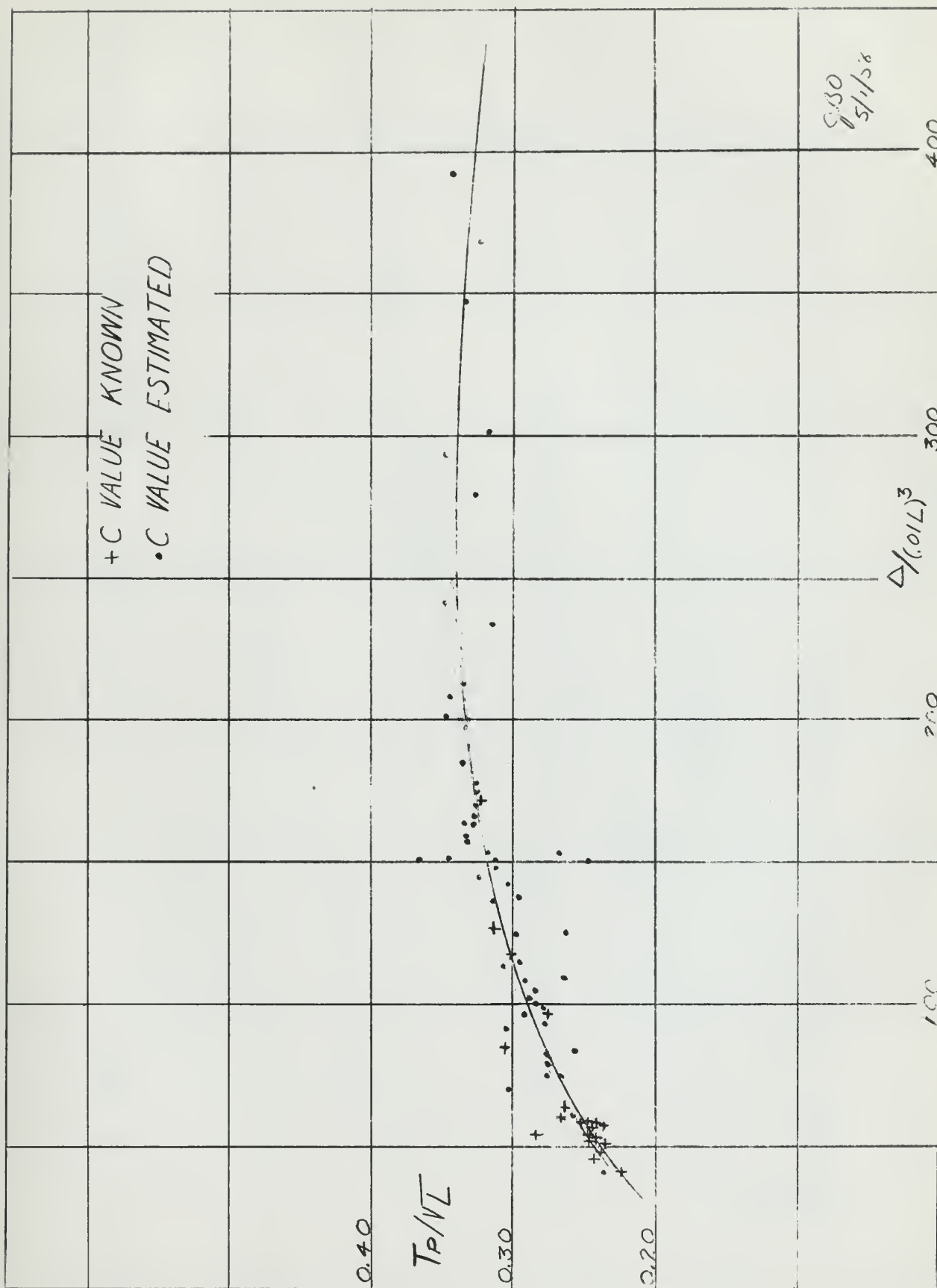
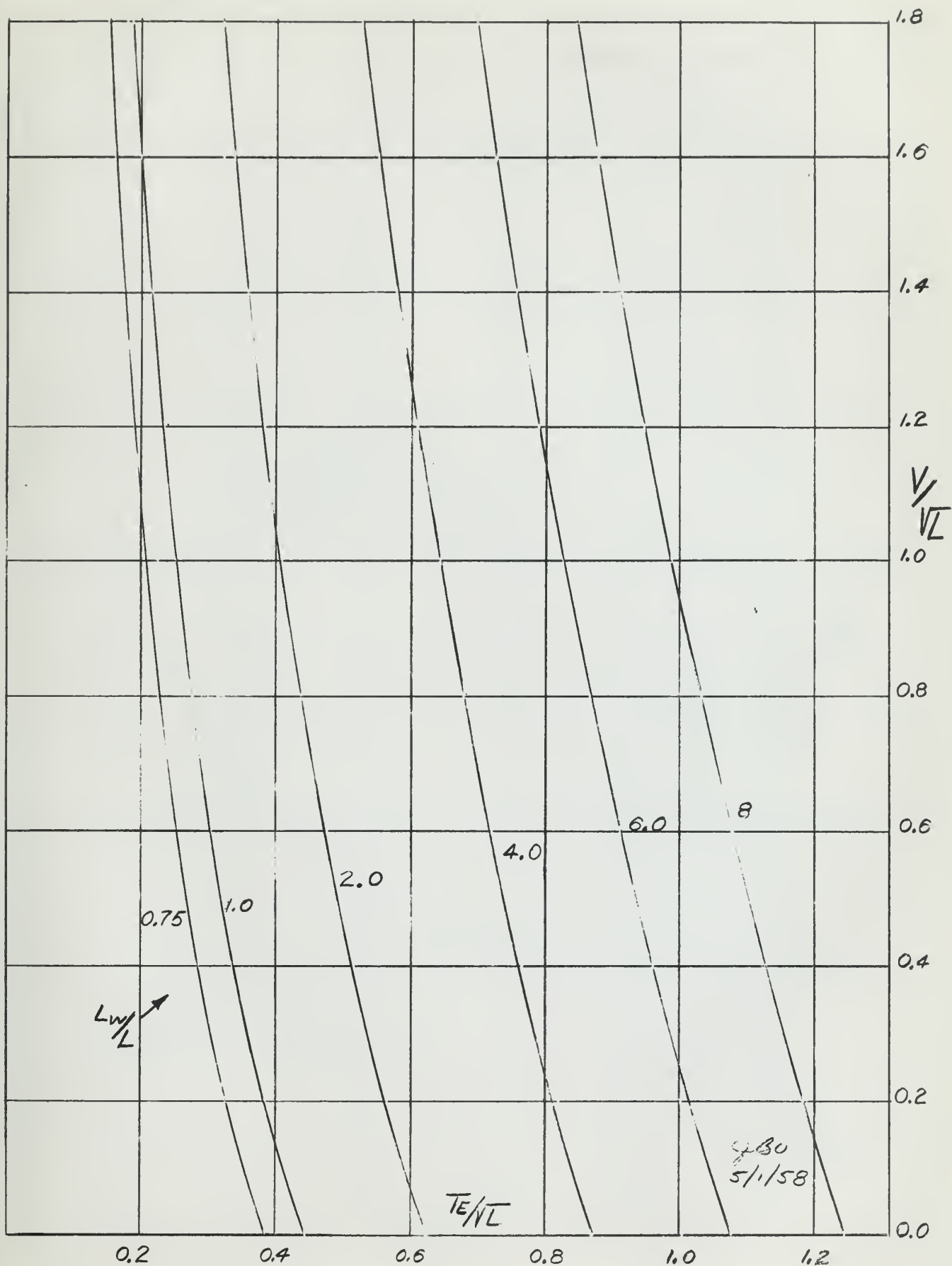




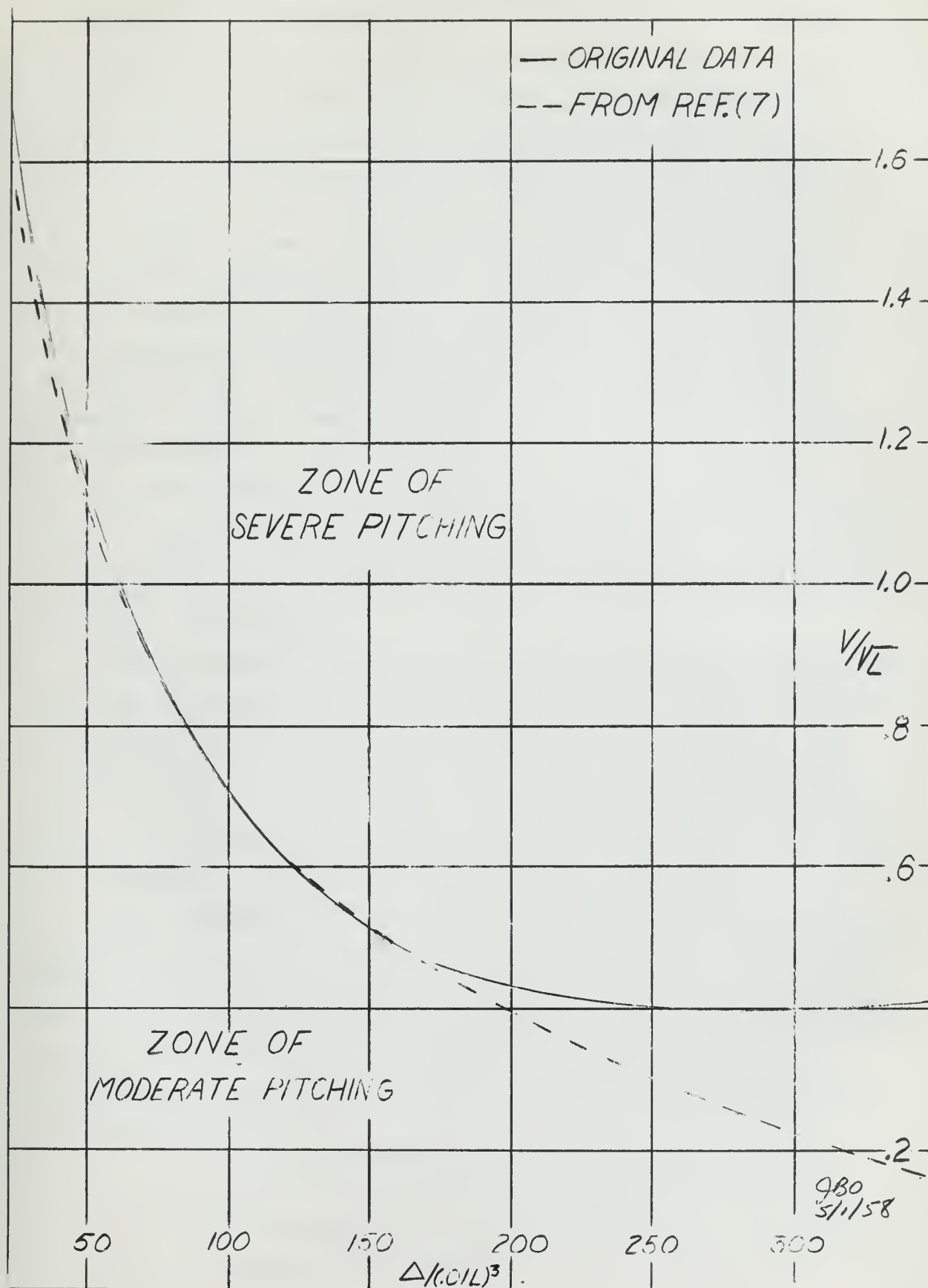
FIGURE IV  
CONDITIONS OF SYNCHRONOUS PITCHING





# FIGURE V

## SYNCHRONOUS PITCHING IN REGULAR HEAD SEAS







## DISCUSSION

The formula (11) for predicting the constant of proportionality,  $C_k$ , was tested on seventy-nine actual vessels and six simulated hull forms based on ellipsoids. The predicted values of  $C_k$  for these ships were obtained with the aid of figures VII, VIII, and IX. In all of the actual ships the value of the factor  $n$  was equal to one or very closely so. The value can not be less than one. In the six ellipsoids, the value of  $n$  was computed and applied. The actual or computed value of  $C_k$  for these ships was obtained by computing the value of the natural pitching period by the standard formula (4). The computed value of  $C_k$  was then obtained and compared to the predicted value and the error calculated. Figure I and Table I show the error distribution for these eighty-five cases.

As can be seen from Table I, the error in predicting  $C_k$  and therefore  $T_p / \sqrt{L}$ , is within the range of -5% to +7% for the great majority of the cases. Only four of the vessels exceed this error range. Each of these four cases represents ships of very high displacement-length ratio and very short actual length.

Whenever weight data was not available for any ship, an approximation was used to estimate  $I_y$  in order to compute  $T_p / \sqrt{L}$ . This assumption was that similar types of ships will be loaded in a similar manner. An average value of  $c$  was obtained for each type of ship for which weight data was available. These values of  $c$  were applied to similar ships for which no weight data was available. A value of  $c$  equal to 1.00 was used in the cases where there was a complete lack of weight data.

In the nonmenclature used in this study, a positive error in  $C_k$  represents a lower  $T_p / \sqrt{L}$  ratio than was predicted. As can be seen from Figure I, the error distribution is slightly skewed to a positive error. The errors represented by this table can be accounted for by the approximations used in developing the formulas for  $f$  and  $h$  (6)(9). The derivation of these factors is covered in Appendix A and includes the following approximations:

- a. The sectional area curve can be represented by two symmetrical triangles and a rectangle.
- b. The waterplane shape can be represented by two symmetrical triangles and a rectangle.



- c. The ratio of the mass moment of inertia of the load to that of the displaced volume is equal to one.
- d. The value of  $(C_w \pm^2 - d^2)$  is negligible.

These conditions can only be approximately true for any ship and therefore the predicted value of  $C_k$  can be only approximately accurate. The small spread of the errors in these eighty-five cases however, indicates that the formula for  $C_k$  (11) can be used to predict the result of a change in the hull form parameters on the natural pitching period.

In accordance with the theory presented by Lewis [7], present day ships operate in a subcritical condition in heavy seas. In accordance with this theory, the smaller the  $T_p / \sqrt{L}$  ratio a ship has, the higher the speed-length ratio it can reach and still remain in a subcritical condition. It is, therefore, advantageous from the point of view of maintaining a higher speed in rough seas to have as low a value of  $T_p / \sqrt{L}$  as possible. At any fixed value of displacement-length ratio, a lower value of  $T_p / \sqrt{L}$  can be obtained by attaining a lower value of  $C_k$ . Since  $C_k$  depends on the factors  $f$  and  $h$ , the effect of the variation of the hull form parameters can be obtained from formulas (6) and (9).

These formulas, (6) and (9), indicate that the dimensions of the ship which are important in changing the value of  $C_k$  are the draft and the waterplane area. Increasing the draft and the waterplane area of a design decreases the  $T_p / \sqrt{L}$  ratio. For a design with constant length, beam and displacement, an increase in the draft and the waterplane area implies an approach to V-form sections. This may be one explanation for the fact that V-form ships exhibit better seakeeping characteristics. It is more likely however, that the increased damping associated with V-form sections may be a more important consideration. This, however, does reinforce the desirability of V-form sections from a seakeeping standpoint.

In the design of most ships, the draft is limited by physical considerations. In addition, the maximum waterplane area that may be obtained is limited. It has also been design practice to attain the maximum practical draft in most sea going ships. This implies that only small variations can be expected in the value of  $C_k$  for ships at any displacement-length ratio. This is borne out by Figure II in which the





computed value of  $C_k$  for the seventy-nine ships is plotted versus the displacement-length ratio. The scatter about the empirical curve drawn through these points is definitely limited. Since a wide variety of ships was studied, this curve indicates that only minor variations in  $C_k$  can be obtained once the displacement-length ratio is fixed.

Figure III shows a plot of  $T_p / \sqrt{L}$  versus the displacement-length ratio. The results obtained from the study of the seventy-nine ships are plotted on this curve and the empirical curve of Figure II is shown. This line represents the average variation of  $T_p / \sqrt{L}$  with the displacement-length ratio and is strictly an empirical result of past practices in ship design. Figure III, when combined with the plot of  $T_e / \sqrt{L}$  versus the speed-length ratio shown in Figure IV results in a curve of the speed-length ratio versus the displacement-length ratio shown in Figure V. The curve given by Lewis [ 7 ] is also plotted on this figure for purposes of comparison. It can be seen that they agree closely except at high displacement-length ratios. The exact position of the curve at high displacement-length ratios is not conclusive due to the scarcity of data of actual ships.

In order to determine the accuracy of the factor  $n$  in formula (7), an ellipsoid of six hundred feet in length and sixty feet in diameter was studied at various drafts from thirty to fifty-six feet. As the draft increases, the value of the factor  $n$  increases due to the difference between the waterline length and beam and that of the submerged hull. The predicted values of  $C_k$  were in satisfactory agreement with the computed values. The value of  $C_k$  was of a much higher magnitude than those for normal hull forms. These results indicate that a high value of  $T_p / \sqrt{L}$  can be obtained by going to abnormal hull forms.

In order to operate in a "supercritical" condition, the period of encounter with the longest significant component of a sea must be less than the ship's natural pitching period. In the data presented by Lewis [ 7 ], the wave length of the longest significant component for a forty knot, fully developed sea, is about 2400 feet. This represents a factor of four for a six hundred foot ellipsoid. From Figure IV, it can be seen that the ellipsoid with a draft of fifty-six feet can operate in this sea in the "supercritical" range with a speed-length ratio of



approximately one. This indicates that "supercritical" operation is not necessarily limited to the future but may be obtained at the present time.

The deeply submerged ellipsoid type of hull form may not be satisfactory for many reasons. A feasibility study of this type of hull must investigate the areas of transverse stability, resistance, reserve buoyancy, the hull form above the waterline and other features. For many purposes, this type of hull would not be satisfactory since the access for cargo handling is limited, the deck space for passengers is limited and the large draft would limit the movements of the vessel. For a tanker, however, many of these disadvantages are not as important as they are for other types. The cargo is handled by piping which reduces the need of access to the below deck spaces. Passengers are not carried and deck space is not essential for the crew. Even the large draft is not critical since tankers frequently load and unload outside of shallow harbors. A feasibility study of this type of hull form may prove to be worthwhile.





## CONCLUSIONS

1. The formula,  $C_k = 0.00655(f)(h)(n)$ , is not accurate for vessels of very high displacement-length ratios and small actual lengths.
2. The formula,  $C_k = 0.00655(f)(h)(n)$ , is sufficiently accurate to be used to predict the effect of variations in hull form parameters on the natural pitching period.
3. The significant methods of reducing the  $T_p / \sqrt{L}$  ratio at any displacement-length ratio are to increase the draft and the waterplane area. This implies that V-form sections are advantageous in decreasing the  $T_p / \sqrt{L}$  ratio as well as to provide increased damping of motion.
4. The curve denoting the critical condition of operation (Fig. V) agrees very closely with Lewis' curve [7] at the lower displacement-length ratios, but shows a marked difference at high displacement-length ratios.
5. The  $T_p / \sqrt{L}$  ratio can be markedly increased by decreasing the length and beam at the waterline in relation to the maximum length and beam of the submerged volume.
6. Large values of  $T_p / \sqrt{L}$  make "supercritical" operation possible for ships with the speed-length ratios which are obtainable at the present.



## RECOMMENDATIONS

1. The effect of ship velocity on the coefficient of accession to inertia should be studied.
2. The effect of damping, coupling to heave, and large pitching angles on the natural pitching period should be studied.
3. Weight distribution data was available for only a few ships other than naval ships. The mass moment of inertia for a large variety of ships should be obtained to verify the approximations used for the constant  $c$ .
4. A greater number of ships should be studied at the high displacement-length ratios.
5. A study should be undertaken to determine the feasibility of a hull form designed for supercritical operation. This type of hull may prove satisfactory for a tanker type ship.



APPENDIX

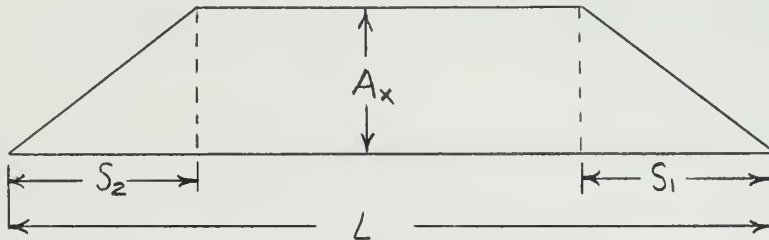


## APPENDIX A

### DETAILS OF PROCEDURE

Development of approximation for  $\sqrt{\frac{k_v^2}{\propto L}}$

Assuming that the shape of the sectional area curve can be approximated as:



For  $S_1 = S_2 = S$  :

$$\nabla = A_x(L - S)$$

$$\text{and } C_p = \frac{\nabla}{A_x L} = 1 - \frac{S}{L}$$

then:

$$35 I_{xs} = \frac{A_x}{12} (L - 2S)^3 + \frac{2A_x}{36} (S)^3 + A_x S \left( \frac{L}{2} - \frac{2}{3}S \right)^2$$

which reduces to

$$35 I_{xs} = \frac{A_x}{12} (L^3 - 3L^2S + 4S^2L - 2S^3)$$

$$\frac{35 I_{xs}}{A_x L^3} = \frac{1}{12} \left( 1 - 3\left(\frac{S}{L}\right) + 4\left(\frac{S}{L}\right)^2 - 2\left(\frac{S}{L}\right)^3 \right)$$

$$\text{since } \frac{S}{L} = 1 - C_p$$





$$\frac{35 I_{xs}}{A_x L^3} = \frac{C_p}{12} (2 C_p^2 - 2 C_p + 1)$$

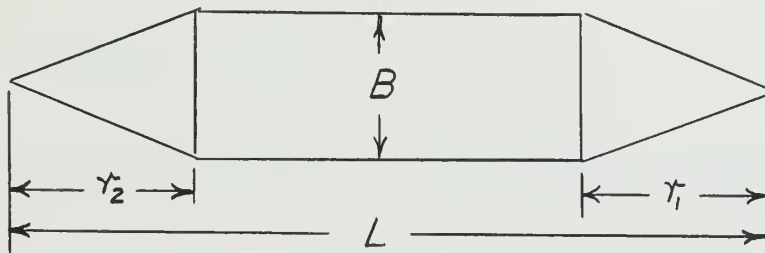
$$\text{but } I_{xs} = \frac{\nabla}{35} K_{xs}^2 = \frac{C_p A_x L^3}{35} k_{xs}^2$$

therefore

$$k_{xs}^2 = \frac{1}{12} (2 C_p^2 - 2 C_p + 1)$$

where  $k_{xs}$  is the gyradius about the midship section for a symmetrical hull form, divided by the length.

Assuming that the waterplane shape can be approximated as:



For  $r_1 = r_2 = r$ :

$$J_{xs} = \frac{B}{12} (L - 2r) + \frac{2B}{36} (r)^3 + B r \left( \frac{L}{2} - \frac{2}{3} r \right)^2$$

since  $A_{WP} = B (L - r)$

$$C_W = \frac{A_{WP}}{BL} = 1 - \frac{r}{L}$$

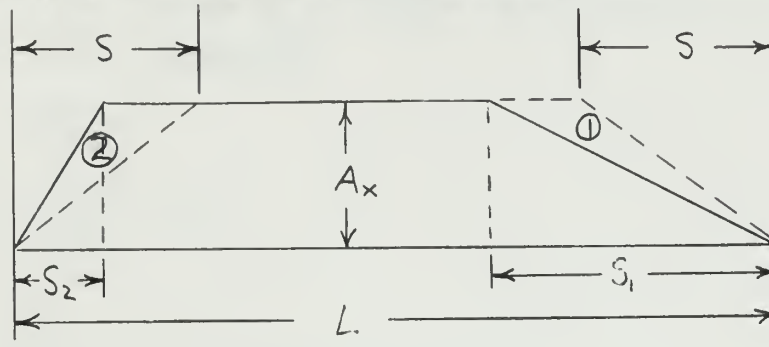
and  $J_{xs} = \alpha_{xs} BL^3$

$$\frac{J_{xs}}{BL^3} = \alpha_{xs} = \frac{C_W}{12} (2C_W^2 - 2C_W + 1)$$



where  $\alpha$  is the longitudinal moment of inertia coefficient taken about the  $x_s$  midship section, for a symmetrical waterplane shape.

For the more complicated, unsymmetrical case, it is assumed that the sectional area curve can be approximated as:



where  $S_1 \neq S_2$  and  $S$  is defined as  $S = \frac{S_1 + S_2}{2}$

$$\nabla = A_x \left( L - \frac{S_1}{2} - \frac{S_2}{2} \right) = A_x (L - S)$$

$$C_P = 1 - \frac{1}{2} \left( \frac{S_1}{L} \right) - \frac{1}{2} \left( \frac{S_2}{L} \right)$$

Defining the area of triangle 1 as  $A_1$  and the area of triangle 2 as  $A_2$

$$A_1 = A_2 = A$$

then

$$35 I_x = 35 I_{xs} + 35 I_2 - 35 I_1 + A_2 (x_2 L)^2 - A_1 (x_1 L)^2$$

where

$I_x$  is the mass moment of inertia of the unsymmetrical area about the midship section

$I_2$  and  $I_1$  are the mass moments of inertia of the areas 2 and 1 about their own centroids.

$I_{xs}$  is the mass moment of inertia of an equal, symmetrical area

$x_2$  and  $x_1$  are the distances from the centroids of areas 2 and 1 to the midship section divided by the length.

Also assuming that

$$I_2 - I_1 \approx 0$$



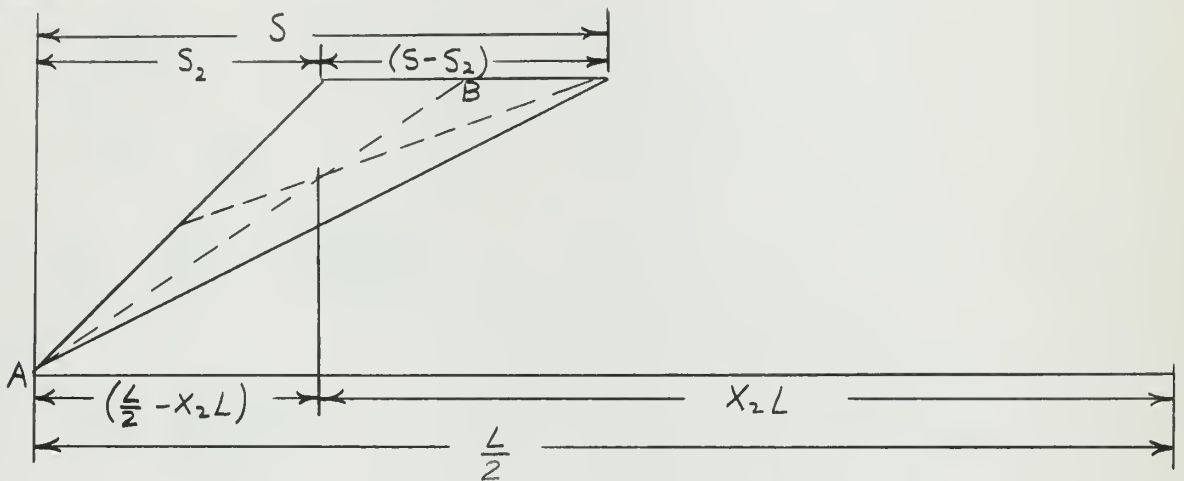
and  $d \nabla = A_2 x_2 + A_1 x_1$

where  $d$  is the distance from the longitudinal center of buoyancy to the midship section divided by the length.  $d$  is defined as negative when the LCB is aft of amidships.

Since  $35 I = \nabla L^2 k^2$

$$k_x^2 = k_{xs}^2 + d (x_2 - x_1)$$

For area 2



by similar triangles

$$\frac{\frac{L}{2} - x_2 L}{\frac{2}{3} \overline{AB}} = \frac{S_2 + \frac{S-S_2}{2}}{\overline{AB}}$$

and  $x_2 = \frac{1}{12} \left[ 6 - 2 \left( \frac{S_1}{L} \right) - 6 \left( \frac{S_2}{L} \right) \right]$

by symmetry

$$x_1 = \frac{1}{12} \left[ 6 - 6 \left( \frac{S_1}{L} \right) - 2 \left( \frac{S_2}{L} \right) \right]$$



$$(x_2 - x_1) = \frac{1}{3} \left[ \frac{s_1}{L} - \frac{s_2}{L} \right]$$

$$(x_2 + x_1) = \frac{1}{12} \left[ 12 - 8 \left( \frac{s_1}{L} \right) - 8 \left( \frac{s_2}{L} \right) \right]$$

$$\text{since } C_P = 1 - \frac{1}{2} \left( \frac{s_1}{L} \right) - \frac{1}{2} \left( \frac{s_2}{L} \right)$$

$$16 C_P - 4 = 12 - 8 \left( \frac{s_1}{L} \right) - 8 \left( \frac{s_2}{L} \right)$$

$$(x_2 + x_1) = \frac{1}{3} (4 C_P - 1) = \frac{d \nabla}{A}$$

$$\frac{\nabla}{A} = \frac{L A_x C_P}{\frac{A_x}{4} (s_1 - s_2)}$$

$$\text{and } \frac{1}{3} \left( \frac{s_1}{L} - \frac{s_2}{L} \right) = \frac{(4 C_P) d}{4 C_P - 1}$$

therefore

$$(x_2 - x_1) = \frac{(4 C_P) d}{4 C_P - 1}$$

and

$$k_x^2 = k_{xs}^2 + \frac{(4 C_P) d^2}{4 C_P - 1}$$

by similarity, for an unsymmetrical waterplane:

$$\alpha_x = \alpha_{xs} + \frac{4 C_w^2 \pm^2}{4 C_w - 1}$$

where:

$\alpha_x$  is the longitudinal moment of inertia coefficient of an unsymmetrical waterplane about the midship section.

$\alpha_{xs}$  is the longitudinal moment of inertia coefficient of a symmetrical waterplane of equal area, about the midship section.

$\pm$  is the distance from the longitudinal center of flotation to the midships section divided by the length.





$$k_v^2 = k_x^2 - d^2$$

$$\alpha_L = \alpha_x - C_w i^2$$

therefore:

$$\frac{k_v^2}{\alpha_L} = \frac{k_{xs}^2 + \frac{4 C_P d^2}{4 C_P - 1} - d^2}{\alpha_{xs} + \frac{4 C_w^2 i^2}{4 C_w - 1} - C_w i^2}$$

and

$$\frac{k_v^2}{\alpha_L} = \frac{k_{xs}^2 + \frac{d^2}{4 C_P - 1}}{\alpha_{xs} + \frac{C_w i^2}{4 C_w - 1}}$$

and approximately

$$\frac{k_v^2}{\alpha_L} \approx \frac{k_{xs}^2}{\alpha_{xs} + \frac{C_w i^2}{4 C_w - 1} - \frac{d^2}{4 C_P - 1}}$$

since  $C_P \approx C_w$

$$\frac{k_v^2}{\alpha_L} \approx \frac{k_{xs}^2}{\alpha_{xs}}$$

when  $C_w i^2 - d^2 \approx 0$

and therefore:

$$\left( \frac{k_v^2}{\alpha_L} \right)^{1/2} = \left[ \frac{2 C_P^2 - 2 C_P + 1}{C_w (2 C_w^2 - 2 C_w + 1)} \right]^{1/2}$$



$$\text{Values of } C = \frac{I_y}{I_v}$$

The following data represents the results obtained from computations of  $I_y$  and  $I_v$  for the twenty ships for which complete data was available. From these results, predictions for the value of  $C$  were made for the remaining vessels. The value of  $C$  used was determined as an average for the ships of similar type. For those types of vessels for which no weight data was available, a value of  $C = 1.0$  was used.

TABLE II

VALUES OF  $C$

Ship	C	Ship	C
Destroyers		Miscellaneous	
DD348	1.17	CB1	.956
DD356	1.14	CM5	1.03
DD445	1.11		
DD692 (S.H.)	1.155	Battleships	
DD692 (L.H.)	1.071	BB61	.946
DD931	1.45		
		Dry Cargo	
Cruisers		C-4	.993
CA32	1.26		
CA68	1.155	Tankers	
CA139	0.961	Hull No. 4476	.985
CL40	1.135		
CL51	0.962		
CL55	1.08		
CL144	1.07		
Aircraft Carriers			
CV32	1.39		
CVB42	1.49		



FIGURE VI  
COEFFICIENT OF A CESSION TO INERTIA

REPRODUCED FROM REF. [6]

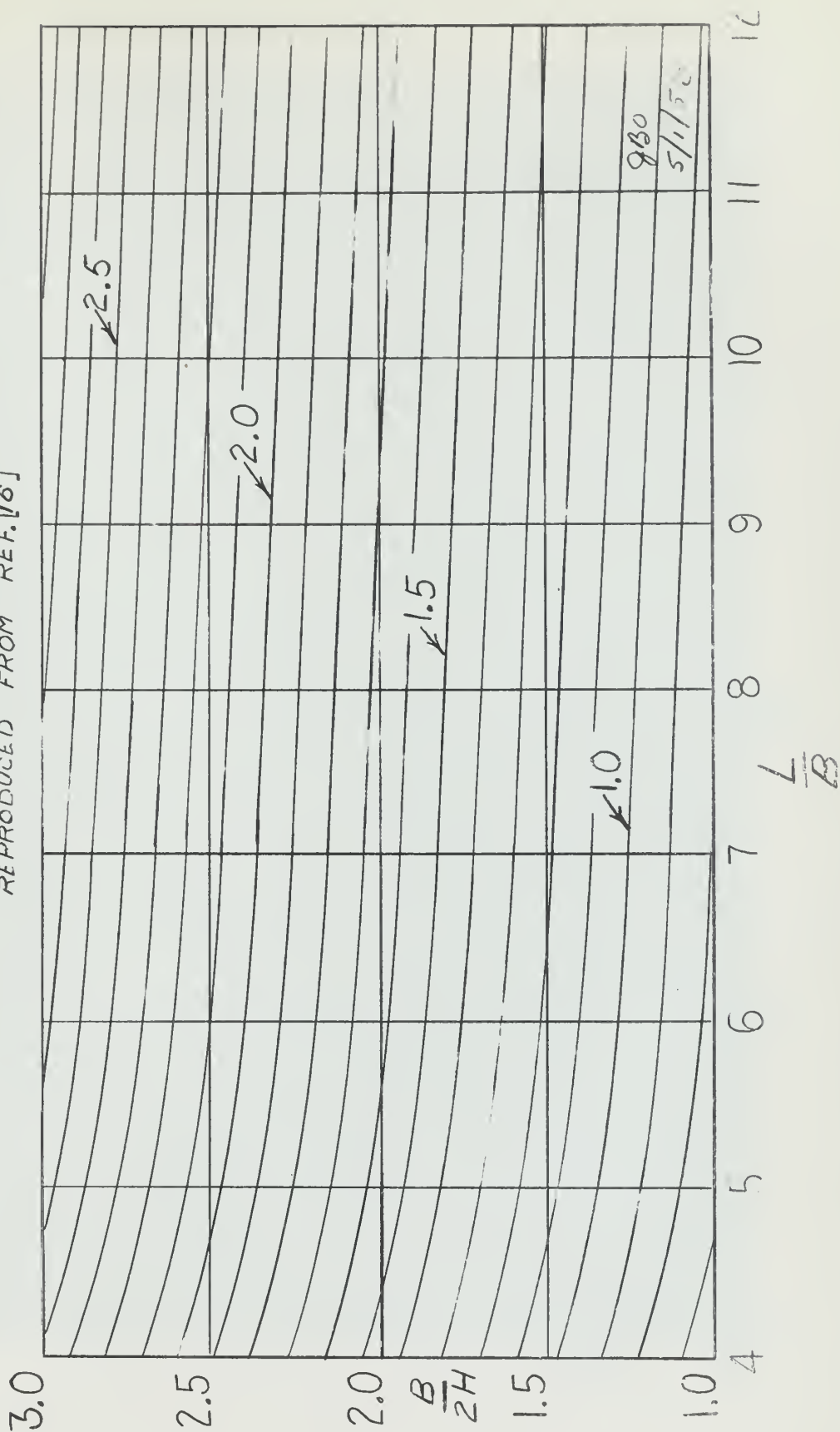






FIGURE VII

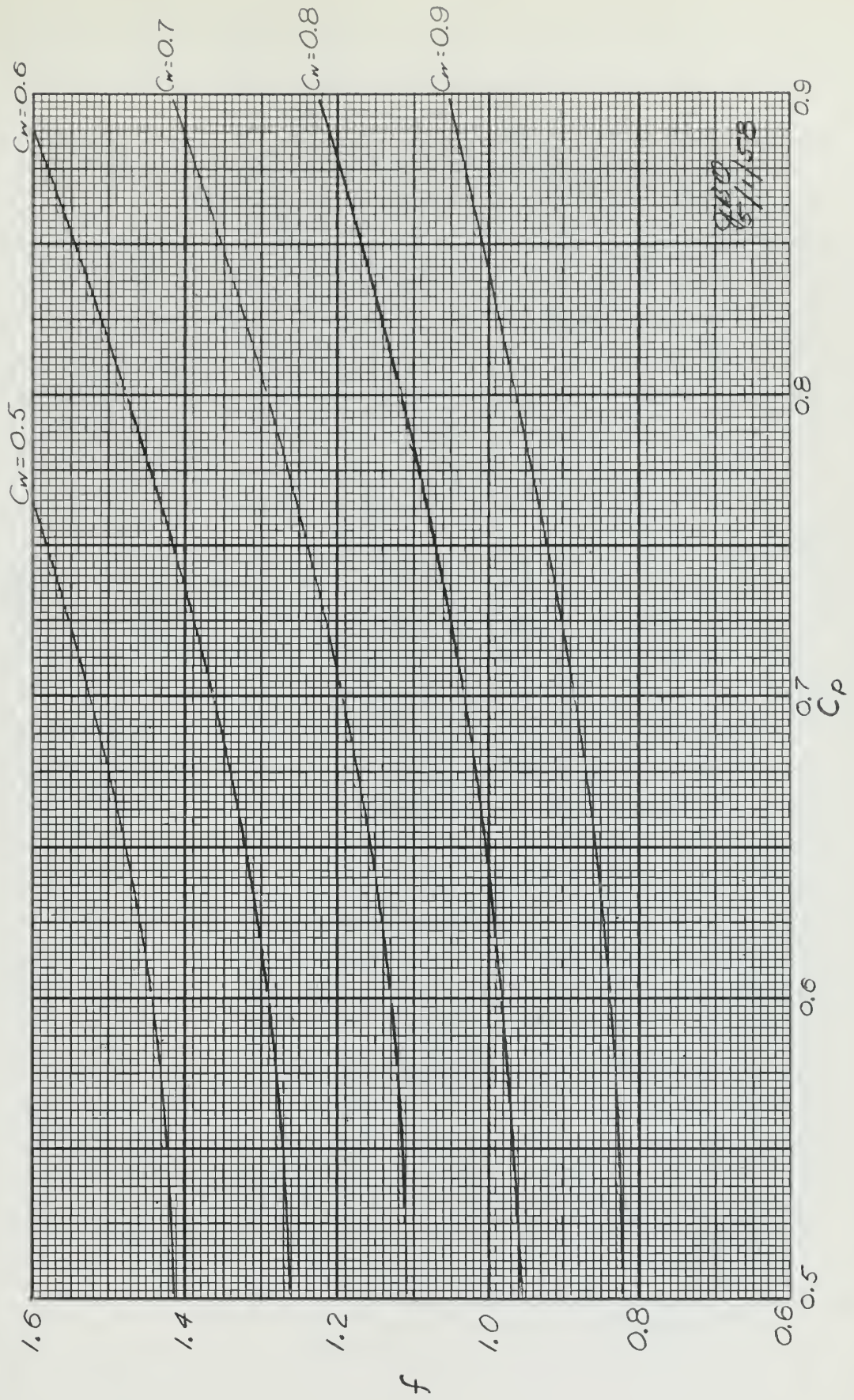






FIGURE VIII

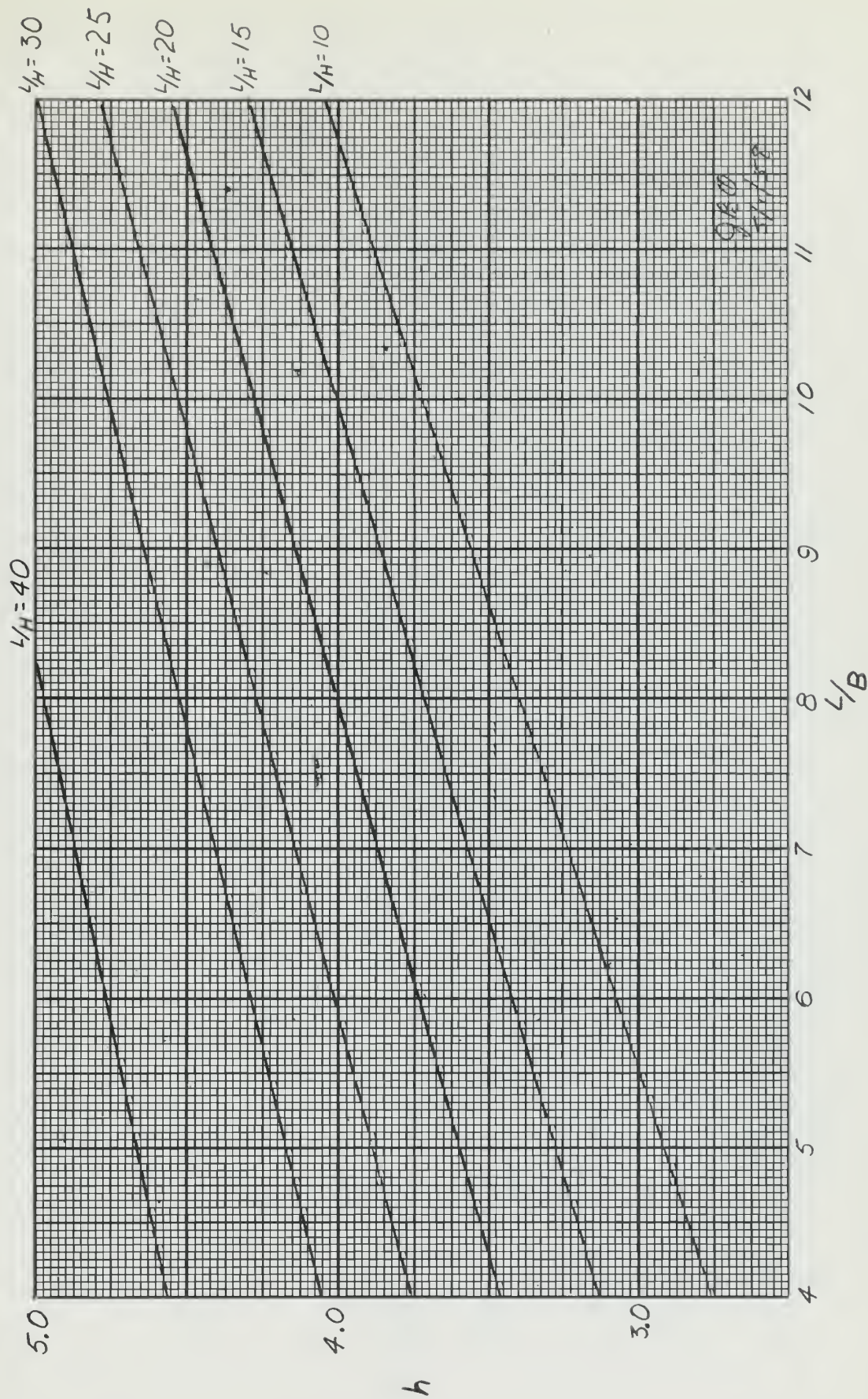






FIGURE IX

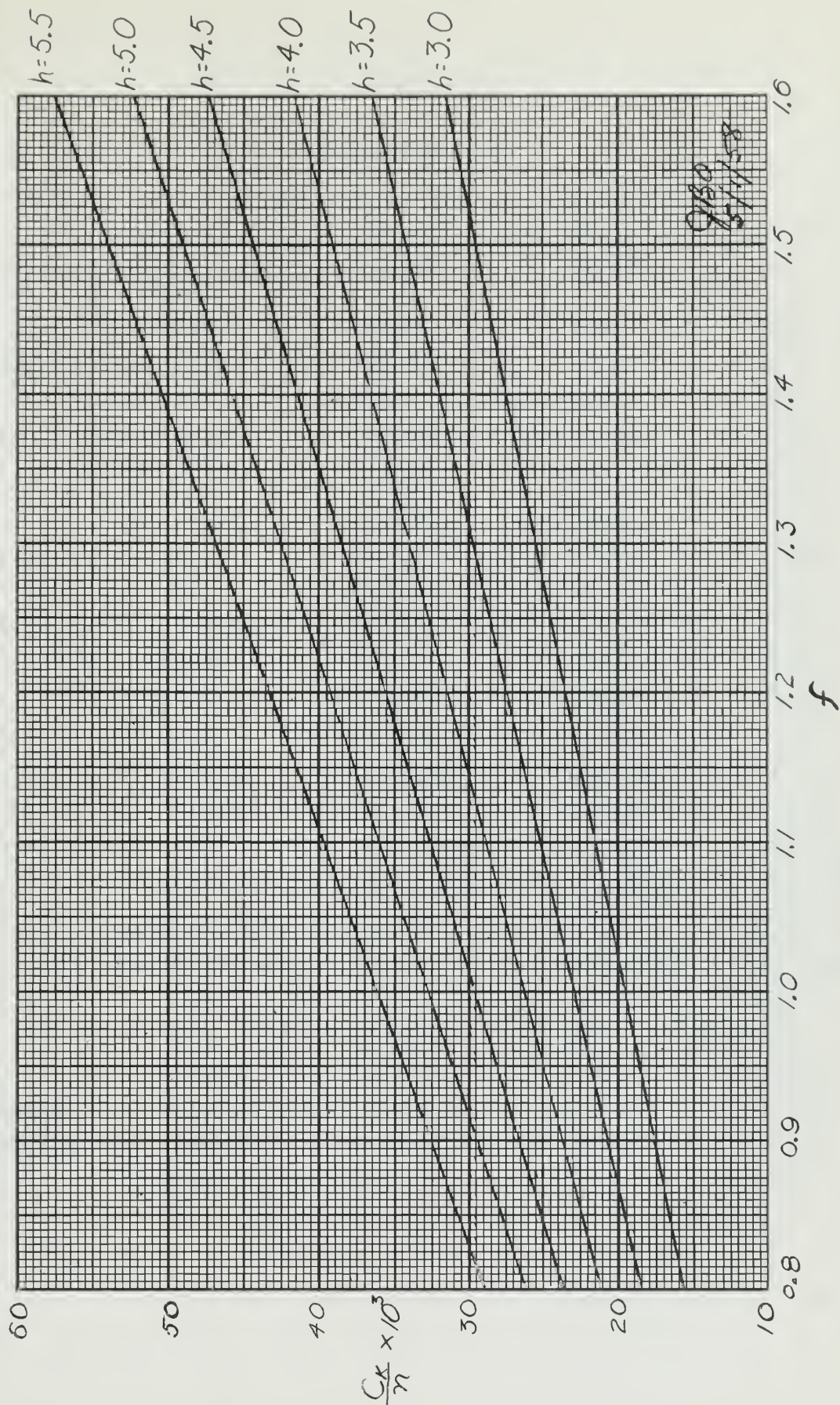




Table III

SUMMARY OF DATA

Ship	No. 1	No. 2	No. 3	No. 4
	CV-4	DD-356	DD-348	CL-51
	Ranger			
$\Delta$	15,742	2105	1725	7400
$\Delta/(\text{.01L})^3$	40.5	40.9	46.3	49.7
L	730.	372.	334.	530
B	73.32	36.58	33.96	52.38
H	20.58	11.25	10.2	19.81
L/B	9.92	10.22	9.85	10.10
B/H	3.56	3.25	3.33	2.64
L/H	35.5	33.1	32.8	26.7
$C_B$	0.456	0.501	0.516	0.500
$C_P$	0.562	0.630	0.620	0.595
$C_X$	0.813	0.795	0.833	0.840
$C_w$	0.671	0.743	0.741	0.740
d	-0.0174	-0.01262	-0.01615	-0.01545
l	-0.0571	-0.03061	-0.05025	-0.0349
$I_y$	--	15,734,461	10,690,061	101,037,294
$I_v$	355,476,786	13,800,000	9,126,230	105,053,020
c	1.40 Assumed	1.140	1.170	0.963
$J_y$	1,029,000,000	80,600,000	51,600,000	314,979,000
$k_{yy}$	1.53	1.39	1.41	1.12
$T_P$	6.39	4.31	4.43	5.46
$T_P/\sqrt{L}$	0.2362	0.2235	0.2425	0.2375
$C_K$ Computed	0.0371	0.0349	0.0357	0.0337
$C_K$ Predicted	0.0390	0.0351	0.0348	0.0360
% Error	+5.11	+0.57	-2.51	+6.82



Ship	No. 5	No. 6	No. 7	No. 8
	DD 445	CV Yorktown	CA 68	CL 40
$\Delta$	2550	23,600	15,153	11,450
$\Delta/(\cdot 01L)^3$	50.7	51.6	51.7	53.0
L	369	770	664	600
B	38.5	81.52	69.6	60.54
H	12.45	24.375	22.0	22.0
L/B	9.60	9.44	9.55	9.92
B/H	3.09	3.35	3.165	2.75
L/H	29.6	31.6	30.2	27.2
C <sub>B</sub>	0.503	0.526	0.523	0.515
C <sub>P</sub>	0.630	0.549	0.614	0.613
C <sub>X</sub>	0.799	0.959	0.852	0.840
C <sub>w</sub>	0.756	0.723	0.744	0.685
d	-0.02115	-0.00965	-0.01175	-0.0697
l	--	--	-0.0695	-0.0725
I <sub>y</sub>	18,977,052	--	349,853,440	220,168,903
I <sub>v</sub>	17,091,344	555,894,590	302,513,768	194,090,040
c	1.110	1.40 Assumed	1.155	1.135
J <sub>y</sub>	85,600,000	1,459,000,000	836,000,000	541,000,000
k <sub>yy</sub>	1.30	1.47	1.33	1.16
T <sub>P</sub>	4.53	6.82	6.20	5.94
T <sub>P</sub> /√L'	0.2360	0.2460	0.2405	0.2421
C <sub>K</sub> Computed	0.0332	0.0343	0.0335	0.0333
C <sub>K</sub> Predicted	0.0333	0.0340	0.0334	0.0329
% Error	+0.31	-0.88	-0.30	-1.20





Ship	No. 9 DD-692 (Long Hull)	No. 10 CL-55	No. 11 CA-139	No. 12 DD-692 (Short Hull)
$\triangle$	3050	11,980	19,560	2880
$\triangle/(\triangle L)^3$	54.3	55.5	57.0	57.3
L	383	600	700	369.
B	40.58	64.96	74.0	40.2
H	13.12	21.75	24.0	13.0
L/B	9.44	9.25	9.45	9.20
B/H	3.09	2.99	3.08	3.09
L/H	29.2	27.6	29.2	28.4
$C_B$	0.526	0.504	0.540	0.521
$C_P$	0.634	0.610	0.614	0.628
$C_X$	0.830	0.826	0.880	0.830
$C_w$	0.766	0.726	0.760	0.757
d	-0.01930	-0.012	-0.00628	-0.0200
l	-0.0584	-0.0681	-0.0675	-0.0607
$I_y$	24,199,375	213,239,213	414,553,319	20,969,821
$I_v$	22,576,160	197,479,000	430,563,487	18,152,334
c	1.071	1.080	0.962	1.153
$J_y$	101,500,000	560,000,000	1,073,100,000	88,600,000
$k_{yy}$	1.30	1.26	1.29	1.28
$T_P$	5.56	5.95	6.22	4.621
$T_P/\sqrt{L}$	0.2843	0.2430	0.2355	0.2405
$C_K$ Computed	0.0329	0.0326	0.0312	0.0318
$C_K$ Predicted	0.0320	0.0334	0.0322	0.0318
% Error	-2.18	+2.45	+3.12	0.0



	No. 13	No. 14	No. 15	No. 16
Ship	DD931	CA 32	CL-144	CV-32
$\Delta$	3900	11,440	17,350	33,500
$\Delta / (.01L)^3$	57.8	59.4	59.4	60.8
L	407.	578	664	820
B	44.96	60.64	68.6	93.80
H	14.5	21.5	24.0	26.0
L/B	9.07	9.52	9.67	8.75
B/H	3.12	2.83	2.86	3.61
L/H	28.1	26.9	27.6	31.5
C <sub>B</sub>	0.515	0.532	0.548	0.586
C <sub>P</sub>	0.633	0.618	0.621	0.604
C <sub>X</sub>	0.813	0.862	0.882	0.972
C <sub>w</sub>	0.757	0.771	0.766	0.723
d	-0.0105	-0.0407	-0.01052	-0.00915
l	-0.0516	-0.00207	-0.0655	-0.0426
I <sub>y</sub>	41,381,622	186,926,000	370,929,537	1,247,666,295
I <sub>v</sub>	31,630,252	148,300,380	347,393,354	898,676,065
c	1.305	1.259	1.069	1.389
J <sub>y</sub>	136,752,000	441,000,000	870,105,600	1,901,088,000
k <sub>yy</sub>	1.29	1.19	1.21	1.50
T <sub>P</sub>	5.07	5.95	6.229	7.66
T <sub>P</sub> / $\sqrt{L}$	0.2520	0.2475	0.2418	0.2680
C <sub>K</sub> Computed	0.0332	0.0321	0.0314	0.0344
C <sub>K</sub> Predicted	0.0319	0.0316	0.0314	0.0342
% Error	-3.92	-1.51	0	-0.60



Ship	No. 17 CVL-48	No. 18 CB-1	No. 19 CV-2 Lexington	No. 20 CVB-42
$\Delta$	17,800	31,725	43,500	54,600
$\Delta/(\text{.01L})^3$	60.9	64.3	70.8	75.0
L	664.	790.	850.	900.
B	75.56	86.0	104.	113.
H	24.0	30.0	30.77	32.0
L/B	8.78	9.19	8.17	7.97
B/H	3.15	2.865	3.39	3.53
L/H	27.7	26.3	27.6	28.1
C <sub>B</sub>	0.512	0.545	0.551	0.587
C <sub>P</sub>	0.619	0.591	0.564	0.605
C <sub>X</sub>	0.829	0.922	0.980	0.971
C <sub>w</sub>	0.741	0.717	0.639	0.718
d	-0.0182	-0.01345	+0.00186	-0.00755
l	-0.0723	-0.0592	--	-0.0480
I <sub>y</sub>	--	842,995,240	--	2,529,130,968
I <sub>v</sub>	379,217,650	880,810,363	1,251,145,588	1,700,839,205
c	1.40 Assumed	0.956	1.40 Assumed	1.489
J <sub>y</sub>	913,332,000	1,702,134,000	1,898,000,000	3,099,600,000
k <sub>yy</sub>	1.30	1.20	1.43	1.46
T <sub>P</sub>	6.94	7.31	8.91	8.31
T <sub>P</sub> /√L	0.2590	0.2602	0.3040	0.2770
C <sub>K</sub> Computed	0.0332	0.0325	0.0362	0.0320
C <sub>K</sub> Predicted	0.0317	0.0330	0.0358	0.0338
% Error	-4.51	+1.51	-1.10	+5.61



Ship	No. 21 Cargo, Ore Sname No. 129	No. 22 Passenger Sname No. 33	No. 23 PG-50	No. 24 Barge, Car Sname No. 148
$\Delta$	15,860	68,324	2420	2010
$\Delta / (.01L)^3$	75.04	79.5	82.9	83.91
L	595.67	950	308	285
B	51.20	100	43.9	44.3
H	20.50	40.0	13.0	10.0
L/B	11.634	9.29	7.02	6.434
B/H	2.497	2.50	3.375	4.429
L/H	29.06	23.75	23.7	28.5
$C_B$	0.887	0.632	0.482	0.539
$C_P$	0.890	0.651	0.576	0.721
$C_X$	0.997	0.970	0.836	0.747
$C_w$	0.925	0.762	0.680	0.817
d	+0.006	-0.001	-0.00162	-0.105
l	-0.002	-0.011	0	-0.053
$I_y$	--	--	--	--
$I_v$	283,768,820	3,037,536,330	9,544,427	8,398,033
c	1.00 Assumed	1.00 Assumed	1.10 Assumed	1.00 Assumed
$J_y$	591,508,960	3,654,166,000	45,250,000	54,602,236
$k_{yy}$	1.09	1.03	1.48	1.85
$T_P$	6.559	8.515	4.83	4.33
$T_P / \sqrt{L}$	0.2688	0.2765	0.2755	0.2570
$C_K$ Computed	0.0310	0.0310	0.0303	0.0281
$C_K$ Predicted	0.0322	0.0308	0.0305	0.0289
% Error	+3.87	-0.64	+0.66	+2.85





Ship	No. 25	No. 26	No. 27	No. 28
	BB-61	LST-1153	Cargo, Orr Sname No. 130	CM-5
$\Delta$	54,400	4600	25,430	7900
$\Delta/(\text{.01L})^3$	85.6	92.3	93.78	97.0
L	860.	368.	647.25	440.
B	108.2	54.0	67.0	60.0
H	34.5	10.0	24.0	18.0
L/B	7.95	6.81	9.66	7.33
B/H	3.14	5.40	2.792	3.33
L/H	24.9	36.8	27.0	24.45
C <sub>B</sub>	0.592	0.811	0.855	0.581
C <sub>P</sub>	0.595	0.811	0.861	0.604
C <sub>X</sub>	0.996	0.9999	0.993	0.964
C <sub>w</sub>	0.696	0.887	0.902	0.733
d	-0.024	-0.014	+0.016	-0.00682
l	--	-0.00136	+0.007	-0.0455
I <sub>y</sub>	1,652,943,200	--	--	67,936,384
I <sub>v</sub>	1,750,042,560	38,621,496	447,869,210	65,898,218
c	0.945	1.00 Assumed	1.00 Assumed	1.015
J <sub>y</sub>	2,394,033,600	162,288,000	820,906,570	197,736,000
k <sub>yy</sub>	1.29	2.32	1.16	1.36
T <sub>P</sub>	8.37	5.823	7.09	5.84
T <sub>P</sub> /√L	0.3059	0.3041	0.2790	0.2785
C <sub>K</sub> Computed	0.0323	0.0317	0.0281	0.0293
C <sub>K</sub> Predicted	0.0331	0.0306	0.0289	0.0300
% Error	+2.48	-3.47	+2.85	+2.38



Ship	No. 29 Passenger Sname No.16	No. 30 Passenger Sname No.21	No. 31 Passenger Sname No.28	No. 32 Passenger Mariposa
$\Delta$	19,900	34957	35,926	25,010
$\Delta/(0.1L)^3$	97.0	99.0	100.38	101
L	590	707	710	628
B	75.5	93.0	96.0	79.0
H	25.0	32.25	32.0	27.0
L/B	7.81	7.60	7.396	7.95
B/H	3.02	2.89	3.000	2.92
L/H	23.60	21.92	22.19	23.21
C <sub>B</sub>	0.617	0.577	0.5765	0.647
C <sub>P</sub>	0.650	0.590	0.5895	0.653
C <sub>X</sub>	0.949	0.979	0.978	0.990
C <sub>w</sub>	0.741	0.727	0.7146	0.745
d	+0.003	0.0	-0.005	-0.00038
l	-0.030	-0.0267	-0.0363	--
I <sub>y</sub>	--	--	--	--
I <sub>V</sub>	314,799,328	727,434,724	755,510,002	441,145,804
c	1.00 Assumed	1.00 Assumed	1.00 Assumed	1.10 Assumed
J <sub>y</sub>	602,841,800	1,235,089,186	1,262,956,237	776,100,000
k <sub>yy</sub>	1.24	1.18	1.22	1.19
T <sub>P</sub>	7.07	7.434	7.552	7.42
T <sub>P</sub> /√L	0.2910	0.2795	0.2834	0.2890
C <sub>K</sub> Computed	0.0296	0.0281	0.0283	0.0289
C <sub>K</sub> Predicted	0.0292	0.0287	0.0292	0.0300
% Error	-1.37	+2.14	+3.90	+3.80



Ship	No. 33 Passenger Sname No.32	No. 34 Cargo, Ore Sname No.128	No. 35 Ferry, Double Ended Sname No.150	No. 36 LST-1
$\triangle$	6726.	12,630.	844.	3610
$\triangle / (.01L)^3$	105.5	108.9	109.7	114.0
L	400.	487.67	197.44	31.6
B	61.0	51.20	38.0	50.0
H	18.0	20.50	10.0	10.0
L/B	6.557	9.526	5.196	6.32
B/H	3.389	2.497	3.800	5.00
L/H	22.22	23.79	19.74	31.6
C <sub>B</sub>	0.536	0.862	0.395	0.805
C <sub>P</sub>	0.566	0.865	0.589	0.806
C <sub>X</sub>	0.947	0.997	0.670	0.998
C <sub>w</sub>	0.701	0.908	0.716	0.895
d	-0.0083	+0.009	0.0	-0.0142
l	-0.036	-0.001	0.0	0.0
I <sub>y</sub>	--	--	--	--
I <sub>v</sub>	42,750,585	151,312,667	1,270,534	21,873,670
c	1.00 Assumed	1.00 Assumed	1.00 Assumed	1.00 Assumed
J <sub>y</sub>	135,595,354	318,170,718	9,883,843	96,222,000
k <sub>yy</sub>	1.37	1.04	1.49	2.09
T <sub>P</sub>	5.659	6.452	3.705	5.48
T <sub>P</sub> /√L	0.2830	0.2919	0.2640	0.3080
C <sub>K</sub> Computed	0.0275	0.0279	0.0252	0.0289
C <sub>K</sub> Predcited	0.0268	0.0289	0.0265	0.0284
% Error	-2.55	+3.60	+5.16	-1.73



Ship	No. 37 LSM-1	No. 38 BB-55	No. 39 Passenger Sname No. 37	No. 40 AD-32
$\Delta$	875	42,061	13,666	16,800
$\Delta/(0.1L)^3$	115.1	115.8	118.8	119.5
L	196.5	714	486.2	520
B	34.0	104	56.0	73
H	6.00	31.5	24.0	24
L/B	5.78	6.85	8.679	7.13
B/H	5.67	3.30	2.338	3.04
L/H	32.75	22.67	20.26	21.65
C <sub>B</sub>	0.764	0.623	0.732	0.645
C <sub>P</sub>	0.767	0.623	0.737	0.655
C <sub>X</sub>	0.995	1.000	0.992	0.985
C <sub>w</sub>	0.900	0.705	0.801	0.750
d	-0.0272	-0.01675	-0.0192	-0.00549
l	-0.0206	--	-0.028	--
I <sub>y</sub>	--	--	--	218,657,700
I <sub>v</sub>	15,759,987	898,173,612	159,313,663	187,432,560
c	1.00 Assumed	0.945 Assumed	1.00 Assumed	1.165
J <sub>y</sub>	16,500,000	1,415,000,000	299,484,384	406,879,200
k <sub>yy</sub>	2.42	1.35	0.94	1.23
T <sub>P</sub>	4.146	7.906	6.655	6.87
T <sub>P</sub> /√L	0.2955	0.2956	0.3018	0.3015
C <sub>K</sub> Computed	0.0276	0.0274	0.0277	0.0276
C <sub>K</sub> Predicted	0.0272	0.0292	0.0281	0.0292
% Error	-1.45	+6.57	+1.44	+5.79





Ship	No. 41 Passenger Sname No.47	No. 42 Launch, Survey Sname No.143	No. 43 Cargo C-4	No. 44 Passenger and Freight Sname No.49
$\Delta$	8518.	75.85	18,610	28,353.
$\Delta / (.01L)^3$	125.125	125.51	126.3	128.69
L	408.	84.57	528.	607
B	62.0	16.31	76.	80.0
H	20.33	4.52	27.	30.0
L/B	6.581	5.186	6.95	7.5328
B/H	3.051	3.106	2.815	2.6535
L/H	20.07	18.70	19.55	20.23
C <sub>B</sub>	0.5797	0.365	0.6125	0.6812
C <sub>P</sub>	0.5988	0.613	0.6246	0.7050
C <sub>X</sub>	0.9682	0.595	0.9807	0.9663
C <sub>w</sub>	0.7234	0.720	0.7236	0.7738
d	-0.0013	-0.011	-0.0149	+0.0041
l	-0.033	-0.037	-0.0349	-0.0115
I <sub>y</sub>	--	--	232,347,357	--
I <sub>v</sub>	60,048,458	24,051.	233,936,260	511,124,401
c	1.00 Assumed	1.00 Assumed	0.99	1.00 Assumed
J <sub>y</sub>	156,613,571	391,410.	393,845,760	762,449,107
k <sub>yy</sub>	1.22	1.19	1.12	1.05
T <sub>P</sub>	6.042	2.404	7.18	7.677
T <sub>P</sub> /√L	0.2991	0.2613	0.3130	0.3121
C <sub>K</sub> Computed	0.0267	0.0233	0.0278	0.0274
C <sub>K</sub> Predicted	0.0274	0.0260	0.0280	0.0278
% Error	+2.62	+11.0	+0.72	+1.46



Ship	No. 45	No. 46	No. 47	No. 48
	AE-21	Cargo Sname No.6	Tanker Standard Oil	BB Pennsylvania
$\Delta$	15,700	12,350	22,907	31,400
$\Delta/(\text{.01L})^3$	136	137.5	142	145.3
L	487	448	544	600
B	72.0	61.0	75.0	96.67
H	26.5	26.5	29.83	28.7
L/B	6.76	7.35	7.25	6.21
B/H	2.72	2.30	2.51	3.37
L/H	18.4	16.9	18.20	20.9
C <sub>B</sub>	0.592	0.598	0.684	0.650
C <sub>P</sub>	0.601	0.625	0.696	0.666
C <sub>X</sub>	0.985	0.956	0.982	0.975
C <sub>w</sub>	0.720	0.743	0.772	0.724
d	-0.065	+0.008	-0.010	-0.010
l	-0.048	-0.028	--	-0.020
I <sub>y</sub>	--	--	--	--
I <sub>v</sub>	156,553,955	106,606,838	317,429,470	504,246,776
c	1.00 Assumed	1.00 Assumed	0.985 Assumed	0.945 Assumed
J <sub>y</sub>	294,537,600	221,785,295	533,240,000	782,900,000
k <sub>yy</sub>	1.08	0.91	1.01	1.34
T <sub>P</sub>	6.88	6.26	7.14	7.93
T <sub>P</sub> /√L'	0.3120	0.2960	0.3031	0.3240
C <sub>K</sub> Computed	0.0270	0.0253	0.0255	0.0269
C <sub>K</sub> Predicted	0.0268	0.0263	0.0270	0.0278
% Error	-0.74	+3.96	+5.87	+2.97



Ship	No. 49 Cargo Sname No.69	No. 50 BB-43	No. 51 Ferry, Car Sname No.100	No. 52 Cargo Sname No.87
$\Delta$	3592	32,550.	6775	21,423
$\Delta/(\cdot 01L)^3$	147.7	150.2	150.2	150.6
L	290.	600.	356.6	522.
B	43.0	97.40	67.86	70.0
H	16.5	30.5	16.5	27.0
L/B	6.74	6.16	5.255	7.463
B/H	2.60	3.19	4.112	2.592
L/H	17.58	19.65	21.61	19.33
C <sub>B</sub>	0.611	0.625	0.593	0.760
C <sub>P</sub>	0.643	0.652	0.685	0.774
C <sub>X</sub>	0.950	0.959	0.866	0.982
C <sub>w</sub>	0.746	0.710	0.805	0.860
d	-0.0075	+0.00125	0.0	+0.031
l	--	-0.0222	0.0	-0.005
I <sub>y</sub>	--	--	--	--
I <sub>v</sub>	13,452,267	521,040,367	40,417,752	335,721,300
c	1.00 Assumed	0.945 Assumed	1.00 Assumed	1.00 Assumed
J <sub>y</sub>	41,546,033	793,800,000	205,233,440	584,349,993
k <sub>yy</sub>	1.02	1.27	1.62	1.03
T <sub>P</sub>	5.299	7.87	4.70	7.09
T <sub>P</sub> /√L	0.3108	0.3660	0.2490	0.3103
C <sub>K</sub> Computed	0.0256	0.0299	0.0235	0.0252
C <sub>K</sub> Predicted	0.0263	0.0285	0.0250	0.0257
% Error	+2.73	-5.01	+6.38	+1.98



Ship	No. 53	No. 54	No. 55	No. 56
	BB	Motor Sailer	Tanker	Tanker
	Delaware	Sname 149	Sname 115	Sname 53
$\triangle$	20,000	153	4165	33,973
$\triangle/(\cdot 01L)^3$	151	153.4	154.3	157.1
L	510	100	300	600
B	84.84	22.83	49.0	82.5
H	26.95	9.08	14.9	31.4
L/B	6.01	4.380	6.073	7.273
B/H	3.15	2.514	3.312	2.629
L/H	18.9	11.0	20.1	19.11
C <sub>B</sub>	0.595	0.256	0.660	0.765
C <sub>P</sub>	0.608	0.575	0.669	0.769
C <sub>X</sub>	0.979	0.445	0.986	0.994
C <sub>w</sub>	0.687	0.677	0.759	0.830
d	-0.01665	-0.028	+0.006	+0.0138
l	-0.0259	-0.030	-0.001	-0.0049
I <sub>y</sub>	--	--	--	--
I <sub>v</sub>	252,820,505	59,836	16,825,505	670,098,311
c	0.945 Assumed	1.00 Assumed	1.00 Assumed	1.00 Assumed
J <sub>y</sub>	404,830,000	670,385	54,737,000	896,911,362
k <sub>yy</sub>	1.22	0.88	1.32	1.05
T <sub>P</sub>	7.79	2.686	5.535	8.122
T <sub>P</sub> /√L	0.3450	0.2686	0.3196	0.3315
C <sub>K</sub> Computed	0.0273	0.0217	0.0257	0.0264
C <sub>K</sub> Predicted	0.0281	0.0222	0.0262	0.0263
% Error	+2.93	+2.31	+1.94	-0.38





Ship	No. 57 Tanker Sname No.56	No. 58 Cargo Sname No.17	No. 59 Cargo C-2	No. 60 Tanker Sname No.95
$\Delta$	32,620	19,825	13,841	23,066
$\Delta/(0.1L)^3$	159.0	163	164.1	165.8
L	590.	496	438.5	519.
B	82.5	71.5	63.0	72.82
H	32.0	30.0	25.75	30.0
L/B	7.152	6.94	6.96	7.128
B/H	2.577	2.38	2.45	2.425
L/H	18.44	16.53	17.1	17.30
C <sub>B</sub>	0.733	0.654	0.670	0.712
C <sub>P</sub>	0.749	0.665	0.694	0.718
C <sub>X</sub>	0.979	0.9848	0.980	0.992
C <sub>w</sub>	0.810	0.752	0.753	0.793
d	+0.0024	+0.006	+0.01159	-0.0082
l	-0.0106	-0.0172	-0.0068	-0.0213
I <sub>y</sub>	--	--	--	--
I <sub>v</sub>	553,397,382	219,477,841	127,105,064	307,841,696
c	1.00 Assumed	1.00 Assumed	0.99 Assumed	1.00 Assumed
J <sub>y</sub>	744,158,193	342,248,555	222,014,000	464,625,770
k <sub>yy</sub>	1.02	0.94	0.99	0.97
T <sub>P</sub>	8.043	7.32	6.88	7.480
T <sub>P</sub> / $\sqrt{L}$	0.3310	0.3284	0.3340	0.3288
C <sub>K</sub> Computed	0.0262	0.0257	0.0261	0.0255
C <sub>K</sub> Predicted	0.0263	0.0265	0.0272	0.0255
% Error	+0.38	+3.11	+3.45	0.0



Ship	No. 61	No. 62	No. 63	No. 64
	Tanker	Tanker	Cargo, Ore	Cargo
	T-2	Beth-Quincy	Sname 9	Sname 20
$\Delta$	22,893	36,044	8,844	14,820
$\Delta/(\text{.01L})^3$	169.8	171	175	178
L	513.4	595	370.0	436.5
B	70.0	84	64.0	62.0
H	30.58	33	17.5	28.1
L/B	7.34	7.09	5.78	7.04
B/H	2.29	2.55	3.66	2.21
L/H	16.80	18.0	21.14	15.55
C <sub>B</sub>	0.749	0.7649	0.747	0.682
C <sub>P</sub>	0.757	0.7699	0.753	0.691
C <sub>X</sub>	0.989	0.9935	0.9922	0.988
C <sub>w</sub>	0.796	0.8468	0.841	0.791
d	+0.02235	+0.0158	+0.022	+0.001
l	--	--	-0.010	-0.0038
I <sub>y</sub>	--	686,805,000	--	--
I <sub>v</sub>	312,587,749	679,037,000	65,805,040	127,182,631
c	0.985 Assumed	0.985	1.00 Assumed	1.00 Assumed
J <sub>y</sub>	467,000,000	949,570,000	175,885,034	221,336,117
k <sub>yy</sub>	0.93	1.02	1.46	0.88
T <sub>P</sub>	7.42	7.88	6.281	6.819
T <sub>P</sub> /√L	0.3278	0.3215	0.3259	0.3263
C <sub>K</sub> Computed	0.0252	0.0247	0.0246	0.0244
C <sub>K</sub> Predicted	0.0265	0.0250	0.0250	0.0245
% Error	+5.16	+1.42	+1.63	+0.40



Ship	No. 65	No. 66	No. 67	No. 68
	Cargo	Cargo	Tug, Fleet	Cargo
	Sname No.67	Sname No.68	Sname No.80	Sname No.1
$\Delta$	10,585	13,900	149.	12,812
$\Delta/(\cdot 01L)^3$	185.6	191.6	200.1	208
L	385.	416.	195.	395
B	54.0	56.9	39.	60.0
H	24.75	27.15	14.1	27.5
L/B	7.13	7.306	5.078	6.58
B/H	2.181	2.097	2.714	2.18
L/H	15.55	15.32	13.82	14.36
C <sub>B</sub>	0.720	0.750	0.514	0.688
C <sub>P</sub>	0.730	0.760	0.569	0.695
C <sub>X</sub>	0.986	0.987	0.904	0.9896
C <sub>w</sub>	0.811	0.860	0.661	0.785
d	+0.008	+0.021	-0.024	+0.0174
l	-0.0197	+0.0064	--	-0.0117
I <sub>y</sub>	--	--	--	--
I <sub>v</sub>	80,324,858	131,425,140	2,381,522	98,714,444
c	1.00 Assumed	1.00 Assumed	1.00 Assumed	1.00 Assumed
J <sub>y</sub>	149,199,832	228,743,915	8,750,800	167,931,326
k <sub>yy</sub>	0.87	0.85	1.02	0.86
T <sub>P</sub>	6.55	6.760	4.85	6.851
T <sub>P</sub> / $\sqrt{L}$	0.3376	0.3314	0.3475	0.3443
C <sub>K</sub> Computed	0.0248	0.0241	0.0245	0.0238
C <sub>K</sub> Predicted	0.0252	0.0243	0.0252	0.0238
% Error	+1.60	+0.80	+2.85	0.0



Ship	No. 69 Tanker Sname 65	No. 70 Trawler Sname 125	No. 71 Dredge, Harbor Sname 103	No. 72 Trawler Sname 123
$\Delta$	2,217	706	3624	352.0
$\Delta/(\cdot 01L)^3$	213.4	234.5	241.25	270.2
L	212.5	144.4	246.7	110.49
B	37.0	27.1	46.0	22.48
H	13.0	12.8	14.92	10.69
L/B	5.744	5.33	5.363	4.916
B/H	2.842	2.115	3.082	2.102
L/H	16.35	11.30	16.53	10.34
C <sub>B</sub>	0.759	0.493	0.747	0.464
C <sub>P</sub>	0.789	0.615	0.757	0.579
C <sub>X</sub>	0.962	0.801	0.987	0.801
C <sub>w</sub>	0.902	0.757	0.842	0.742
d	+0.0110	+0.008	+0.011	-0.009
l	-0.0165	-0.019	-0.010	-0.013
I <sub>y</sub>	--	--	--	--
I <sub>v</sub>	5,892,512	629,228	11,558,621	171,498
c	1.00 Assumed	1.00 Assumed	1.00 Assumed	1.00 Assumed
J <sub>y</sub>	22,333,004	3,431,341	36,357,972	1,241,394
k <sub>yy</sub>	1.10	0.78	1.19	0.76
T <sub>P</sub>	4.880	3.740	5.463	3.229
T <sub>P</sub> /√L	0.3342	0.3114	0.3475	0.3069
C <sub>K</sub> Computed	0.0219	0.0204	0.0223	0.0187
C <sub>K</sub> Predicted	0.0219	0.0215	0.0231	0.0205
% Error	0.0	+5.40	+3.59	+9.63





Ship	No. 73 Trawler Sname No.111	No. 74 Tug,Ocean Going Sname No.86	No. 75 Tug,Ocean Going Sname No.75	No. 76 Tug, Ocean Going Sname No.94
$\Delta$	613.	1094.	738.5	517.8
$\Delta/(\text{.01L})^3$	279.2	294.	301.3	347.
L	130.	155.0	134.8	114.58
B	28.5	34.7	33.8	30.1
H	12.5	12.8	12.36	11.3
L/B	4.562	4.470	3.992	3.805
B/H	2.280	2.710	2.733	2.665
L/H	10.40	12.11	10.91	10.14
C <sub>B</sub>	0.460	0.556	0.459	0.465
C <sub>P</sub>	0.570	0.677	0.607	0.586
C <sub>X</sub>	0.807	0.821	0.757	0.794
C <sub>w</sub>	0.699	0.776	0.738	0.717
d	+0.001	-0.002	-0.002	-0.004
l	-0.036	-0.0252	-0.0223	-0.0221
I <sub>y</sub>	--	--	--	--
I <sub>v</sub>	407,229.	1,266,469	566,220	277,483
c	1.00 Assumed	1.00 Assumed	1.00 Assumed	1.00 Assumed
J <sub>y</sub>	2,247,498	5,614,318	3,393,202	1,748,920
k <sub>yy</sub>	0.80	0.95	0.91	0.85
T <sub>P</sub>	3.745	4.343	3.694	3.550
T <sub>P</sub> /√L	0.3279	0.3486	0.3179	0.3318
C <sub>K</sub> Computed	0.0196	0.0203	0.0183	0.0178
C <sub>K</sub> Predicted	0.0203	0.0207	0.0194	0.0196
% Error	+3.57	+1.97	+6.01	+10.1



Ship	No. 77 Tug, Harbor Sname 70	No. 78 Tug Sname No. 72	No. 79 Tug, Harbor Sname 73
$\triangle$	27.6	158.7	347.3
$\triangle/(0.1L)^3$	368	392.2	481.5
L	42.1	74.33	87.67
B	12.5	20.48	23.6
H	4.01	8.14	10.8
L/B	3.365	3.623	3.720
B/H	3.120	2.517	2.340
L/H	10.50	9.27	8.118
C <sub>B</sub>	0.458	0.453	0.544
C <sub>P</sub>	0.595	0.589	0.623
C <sub>X</sub>	0.770	0.770	0.873
C <sub>w</sub>	0.757	0.742	0.776
d	-0.020	-0.021	-0.009
l	-0.045	--	-0.034
I <sub>y</sub>	--	--	--
I <sub>v</sub>	2061.3	32,448	119,791
c	1.00 Assumed	1.00 Assumed	1.00 Assumed
J <sub>y</sub>	40,591.3	309,286	722,316
k <sub>yy</sub>	0.98	0.98	0.70
T <sub>P</sub>	2.083	2.95	3.475
T <sub>P</sub> /√L	0.3210	0.3422	0.3717
C <sub>K</sub> Computed	0.0167	0.0174	0.0169
C <sub>K</sub> Predicted	0.0190	0.0180	0.0180
% Error	+13.8	+3.45	+6.5

Ships identified by "Sname" number are from Model and Expanded Resistance Data Sheets No. 1 - 150 of the Society of Naval Architects and Marine Engineers.



Table IV

	(600x60) Ellipsoid	(600x60) Ellipsoid	(600x60) Ellipsoid
Ship	E-1	E-2	E-3
$\Delta$	16154	20,920	25,196
$\Delta/(\text{.01L})^3$	74.8	96.9	116.6
$L_w$	600	583.5	546
$B_w$	60	58.5	54.6
H	30.	36.	42.
$L/B$	10.00	10	10
$B/H$	2.00	1.667	1.429
$L/H$	20	16.67	14.29
$C_B$	0.5235	0.565	0.583
$C_P$	0.665	0.691	0.697
$C_X$	0.7854	0.8171	0.8365
$C_w$	0.7854	0.7854	0.7854
d	0	0	0
l	0	0	0
$I_y$	--	--	--
$I_v$	293,679,720	395,019,430	475,787,159
c	1.0	1.0	1.0
$J_y$	636,336,000	570,641,182	436,378,872
$k_{yy}$	0.82 Assumed	0.68 Assumed	0.58 Assumed
$T_P$	6.003	7.075	8.613
$T_P/\sqrt{L}$	.2450	.2888	.3516
$C_K$ Computed	.0284	.0293	.0326
$C_K$ Predicted	.0283	.0295	.0330
% Error	-0.35	+0.68	+1.23



Table IV (Cont'd.)

Ship	(600x60) Ellipsoid	(600x60) Ellipsoid	(600x60) Ellipsoid
	E-4	E-5	E-6
$\triangle$	28,930	31,421	31,857
$\triangle/(\cdot 01L)^3$	134.0	145.5	147.5
$L_w$	480	360	300
$B_w$	48.	36.	30.
H	48.	54.	56.
$L/B$	10	10	10
$B/H$	1.25	1.11	1.071
$L/H$	12.50	11.11	10.71
$C_B$	0.586	0.566	0.553
$C_P$	0.696	0.685	0.676
$C_X$	0.8420	0.8265	0.7854
$C_w$	0.7854	0.7854	0.8182
d	0	0	0
l	0	0	0
$I_y$	-	-	-
$I_v$	545,962,365	576,491,213	579,025,684
c	1.0	1.0	1.0
$J_y$	260,643,226	82,469,146	39,771,000
$k_{yy}$	0.49 Assumed	0.44 Assumed	0.42 Assumed
$T_P$	11.59	20.76	29.80
$T_P/\sqrt{L}$	.4731	.8473	1.216
$C_K$ Computed	.0409	.0701	0.100
$C_K$ Predicted	.0413	.0723	0.102
% Error	+0.98	+3.14	+2.00





# C - SAMPLE CALCULATION DATA SHEET

SHIP- BB 61

$\Delta_{DWL}$	54,400	L/H	24.9	$C_R$	.592
L	860.	B/H	3.14	$C_P$	.595
B	108.2	L/B	7.95	$C_W$	.096
Hx	34.5	MTI	6628	$C_X$	.996
$A/(C.L.)^3$	85.6	LCF		LCB	-20.7
		$\lambda$		d	-.024

$$I_y = \underline{1,652,943,200}$$

$$I_v = \underline{1,750,042,560}$$

$$J_y = \underline{2,394,033,600}$$

$$k_{yy} = \underline{1.29}$$

$$T_D = \frac{2\pi}{\sqrt{\rho g}} \sqrt{\frac{I_y + k_{yy} I_v}{J_y}}$$

$$T_D = \underline{8.37}$$

$$T_D / L = \underline{.3059}$$

$$C_{K \text{ COMP}} = .0323$$

$$C_{K \text{ PRE}} = .0331$$

$$\text{ERROR} = +2.48\%$$



# COMPUTATION SHEET

SHIP BB61  
COMPUTATION OF  $\Delta$ ,  $I_x$   
 $S = L/20 =$  \_\_\_\_\_

SOURCE OF DATA \_\_\_\_\_  
CONTRACT PLANS \_\_\_\_\_

STA	AREA OR BEAM	SM	f(A)	ARM	f(M)	ARM	f(I)
C	0	1/4	0	10	0	10	0
1	539	1	539	9	4851	9	43659
2	825	3/4	619	8	4952	8	39616
4	1520	2	3040	6	18240	6	109440
6	2468	1	2468	4	9872	4	39488
8	3215	2	6430	2	12860	2	25720
10	3702	1	3702	0	50775	0	0
12	3718	2	7436	-2	14872	-2	29744
14	3395	1	3395	-4	13580	-4	54320
16	2533	2	5066	-6	30396	-6	182376
18	870	3/4	653	-8	5224	-8	41792
19	335	1	335	-9	3015	-9	27135
20	0	1/4	0	-10	0	-10	0
A $\Sigma$		f(A)=	33683		-67087		
B				f(M)=	-16312	f(I)=	593290

$$\cancel{A_{WP}} \text{ OR } \nabla = \frac{4}{3} S f(A) = 1,931,046 \quad \Delta = 55173$$

$$\cancel{LCF} \text{ OR } LCB = S \left[ \frac{f(M)}{f(A)} \right] = -20.7$$

$$\cancel{J_x} \text{ OR } \cancel{35} I_x = \frac{4}{3} S^3 f(I) = 1,771,802,560 @ 54,400 T.$$

$$J_y = J_x - A_{WP} (LCF)^2 =$$

$$I_y = I_x - \nabla (LCB)^2 = 1,750,042,560$$



## COMPUTATION OF $J_y$

$$J_y = 420 \times MTI \times L$$

$$J_y = 420 \times 6628 \times 860$$

$$J_y = 2,394,033,600$$

NOTE: WHERE MTI WAS NOT AVAILABLE,  $J_y$  WAS  
COMPUTED ON FORM ON PAGE 56.



## APPENDIX D

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